

# Hierarchical Clustering and the Butcher-Oemler Effect

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## Abstract

We show that the rapid evolution in the fraction of blue, star-forming galaxies seen in clusters as a function of redshift (the Butcher-Oemler effect) can be explained very simply if structure formation in the universe proceeds hierarchically. We show that a rich cluster observed at high redshift has had a significantly different evolutionary history to a cluster of the same richness observed today. High redshift clusters take longer to assemble and thus undergo more merging at small lookback times. We have investigated two models of star formation in cluster galaxies: 1) a model in which star formation is induced by galaxy-galaxy mergers and interactions and 2) a model in which star formation is regulated by the infall of galaxies onto larger systems such as groups and clusters. Both models produce trends consistent with the Butcher-Oemler effect. Our models of cluster formation and evolution allow us to make predictions about trends in the observed properties of clusters with redshift. We find that there should be a correlation between the mass of the cluster or group and the strength of the observed Butcher-Oemler effect, with more massive systems exhibiting more evolution than less massive systems. We also predict that both the blue galaxy fraction and the incidence of interacting or merging galaxies in rich clusters should rise continuously with redshift. Finally, we have explored the influence of cosmological parameters on our predictions for cluster evolution. We find that models in which structure formation occurs at very early epochs, such as low  $\Omega$  models, predict rather little recent star formation and merging activity in clusters at redshifts around 0.4. Larger observational samples and more detailed modelling will be needed before any firm constraints can be placed on cosmology.

# 1 Introduction

It is now well established that substantial differences exist between nearby clusters and clusters observed at redshifts greater than 0.2. The increase in the number of blue galaxies that occur in concentrated galaxy clusters at high redshift is commonly referred to as the Butcher-Oemler effect, in honour of the two astronomers who first presented photometric evidence for this phenomenon (Butcher & Oemler 1978). Substantial spectroscopic follow-up work on the Butcher-Oemler clusters has since been carried out (Dressler & Gunn 1982,1983; Lavery & Henry 1986; Couch & Sharples 1987, Charlot & Silk 1994). These studies have confirmed that many of the blue, star-forming galaxies are indeed cluster members and not merely interlopers along the line-of-sight. In addition, analyses of the spectra of these galaxies have yielded important clues about the nature of these objects. Approximately 50-60 % of the population show strong emission lines of [OII], [OIII] and  $H\beta$ , indicative of vigorous star formation. The remainder show very strong Balmer absorption lines, but negligible emission lines. These objects also tend to be considerably redder. It has been shown (Dressler & Gunn 1983, Couch & Sharples 1987) that many of the features of these spectra may be understood if these galaxies were subject to a substantial burst of star formation at some point in their histories. The very blue colours of some of the strong emission-line objects require star formation rates considerably higher than those observed in present-day spiral galaxies. The strong absorption-line galaxies have been postulated to be "post-starburst" systems. A post-starburst population would include a large population of A stars contributing to the strong Balmer lines, but if the star formation rate declined rapidly following the burst, it would lack the younger O and B stars that excite the line-emitting gas in HII regions.

The discovery of a sizeable population of star-forming galaxies in high redshift clusters has led to a great deal of speculation about the physical processes that could be responsible for this activity. One popular hypothesis is that mergers or close encounters between the cluster galaxies may be responsible. Lavery & Henry (1988) and Lavery, Pierce & McClure (1992) have presented evidence from ground-based imaging of distant clusters that a substantial fraction of the blue galaxies are either multiple systems or have peculiar morphologies and features, such as tidal tails, suggestive of interactions or mergers. Further support for the merging hypothesis has also come from the first Hubble Space Telescope (HST) observations of distant clusters, which suggest that interactions are responsible for many of the bluest galaxies with the most vigorous star formation (Dressler et al 1994, Couch et al 1994). However, these observations also indicate that approximately half the blue population is composed of fairly ordinary-looking late-type spirals. Dressler & Gunn (1983) have suggested that the infall of gas-rich galaxies into the high-pressure, dense intracluster medium might help trigger starbursts. These galaxies would then be observed as luminous, blue spiral systems. Although recent observational data has shed considerable light on the physical processes responsible for triggering star formation in cluster galaxies, no convincing explanation has yet been given as to *why* there should be a trend in the properties of rich clusters with redshift. As put by Dressler (1993), "the reason(s) for the demise of these actively star-forming systems in the cluster environment by the present epoch remains the major mystery in this field".

In this paper, we study cluster evolution within the framework of the hierarchical clustering picture of structure formation in the universe. In this picture structure forms from the bottom up, via the merging of small objects to form successively larger and larger mass systems. Considerable support for this theory has been accumulating in recent years as astronomical observations of galaxies and clusters have reached to higher redshifts. Perhaps the strongest support for a bottom-up scenario of structure formation has come from X-ray surveys, which find strong evidence for a decline in the abundance of X-ray luminous clusters out to redshifts of  $\sim 1$  (Edge et al 1990, Gioia et al 1990, Henry et al 1992, Castander et al 1993). In addition, many clusters observed in the X-ray show evidence of substructure (see for example Jones & Foreman 1992), indicating that they may have formed recently by the merging of a number of smaller subunits. In this paper, we show that the trend of more star-formation activity in rich clusters at high redshift may be explained naturally within the framework of the hierarchical clustering picture. We show that a cluster that is assembled at high redshift has had a very different merging history to a cluster of the same mass assembled at the present day. High redshift clusters take much longer to form. The increased star-formation activity seen in the cluster galaxies can be explained very simply by the increased merging activity taking place in the dark matter component at an epoch just prior to the time the cluster is observed as single, collapsed object. We explore two simple models for star formation in cluster galaxies. These models are designed to reflect the interaction-driven and infall-driven pictures of star formation discussed above. We show that *both* models lead to trends that are consistent with the observations. We also explore the effect of our choice of cosmological initial conditions on our predictions for cluster evolution. This aim of this paper is to explain the *qualitative* trends seen in the data. A more detailed quantitative analysis is reserved for a later publication.

## 2 The Merging History of Clusters

We use the algorithm developed by Kauffmann & White (1993, hereafter KW) to trace the merging history of a dark matter halo of specified mass present a redshift  $z$ . This algorithm is based on an extension of the Press-Schechter theory due to Bower (1991) and Bond et al (1991). In these papers, expressions were derived for the conditional probability that material in an object of mass  $M_1$  at redshift  $z_1$  would end up in an object of mass  $M_0 > M_1$  at a later redshift  $z_0$ . The algorithm of KW used these probabilities to construct Monte-Carlo realizations of the merging histories of halos. These histories were stored in the form of a *tree* (akin to a family tree), with each successive layer representing a step in redshift and branches indicating the merging paths of the halo's progenitors. The reader is referred to KW for further details.

Let us now consider the merging histories of a set of clusters of fixed mass, which are observed at a series of redshifts:  $z_{obs} = 0, 0.07, 0.15, 0.2, 0.3$  and  $0.4$ . To do this, we trace the evolution of the mass of the *largest cluster progenitor* as a function of lookback time,  $t$ , from the the redshift  $z_{obs}$ . In figure 1(a) we show results for a dark matter halo of mass  $10^{15} M_{\odot}$ , comparable to the mass of a moderately rich cluster. We adopt a cold dark matter

(CDM) cosmology with  $\Omega = 1$ ,  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and bias parameter  $b=2.5$  as our reference model. In section 4, we will discuss the influence of other choices of cosmological initial conditions on our predictions.

The curves in figure 1(a) represent averages over 50 Monte Carlo realizations of the formation history of a  $10^{15} M_\odot$  cluster. As can be seen, the evolutionary history is strongly dependent on  $z_{obs}$ . There are two reasons for this effect. The first is simply that the universe is younger as measured in gigayears at higher redshift. The second is that a rich cluster observed at high redshift results from a much higher amplitude fluctuation in the initial linear density field than a cluster of the same mass seen today. As a result, high redshift assemble considerably later and accrete a much larger percentage of their final mass in the few gigayears just prior to  $z_{obs}$ . In figures 1(b) and 1(c), we show similar curves for halos with mass  $10^{13} M_\odot$  and  $10^{12} M_\odot$  respectively, corresponding to the mass of a galaxy group and to that of a typical bright galaxy. It is clear that halos of lower mass form earlier, a trend which has also been noted by Lacey & Cole (1993). In addition, we also see the difference in the evolutionary history of high and low redshift systems is much smaller for halos of lower mass.

These results may be understood intuitively as follows. In a hierarchical universe, the characteristic mass scale of collapsed objects increases with time. Low mass objects typically form at higher redshift than high mass objects. In addition, the most massive halos present at any given time tend to form via the merging of smaller objects that are close to the characteristic mass at that epoch. This is why rich clusters, which are on the high-mass tail of the distribution of collapsed objects in the universe today, tend to form rather late and via the merging of many smaller, more typical halos. A cluster of the same mass present at high redshift is even further out on the tail of the mass distribution and the effect is correspondingly more severe. Halos with masses corresponding to those of galaxy groups and isolated bright galaxies are much more typical objects at redshifts less than 1, and thus do not display these dramatic trends in their evolutionary history. It is only at very high redshifts, when groups and galaxies become rare objects, that these effects become important.

We have seen that a trend in the evolutionary history of a rich cluster towards later assembly times with increasing  $z_{obs}$ , is a *natural consequence* of hierarchical structure formation. It would also be natural to expect that the observed properties of the galaxies in high redshift clusters should reflect this trend in the dark matter evolution. Late assembly means that considerable merging of the dark matter component has occurred at late evolutionary times, and it is likely that this merging activity would lead to an increased level of star formation (ie the Butcher-Oemler effect) in the cluster galaxies. We will discuss this in more detail in the next section. Another consequence of hierarchical clustering is that the strength of the Butcher-Oemler effect should correlate with the mass of the system. This is evident from figures 1(b) and 1(c), which show that the difference in the evolutionary histories of low mass halos as a function of  $z_{obs}$  is much smaller than that for massive halos. This accords well with recent observational studies of the evolution of galaxies in high redshift groups selected around radio galaxies (Allington-Smith et al 1993). These studies have shown that groups exhibit much weaker evolutionary trends with redshift than do rich clusters.

One very useful feature of our Monte-Carlo approach to calculating the merging history of dark matter halos is that we are able to obtain a measure of the scatter in the evolutionary history of individual clusters. Recall that the curves in figure 1 represent averages over 50 Monte-Carlo realizations. In figure 2, we show individual merging histories for 30 different clusters with mass  $10^{15}M_{\odot}$  and  $z_{obs} = 0.4$ . The thick dashed line shows the average merging history for a  $10^{15}M_{\odot}$  cluster observed at  $z_{obs} = 0$ . As can be seen, the scatter in individual merging histories is rather large and it is interesting to note that a small percentage of clusters with  $z_{obs} = 0.4$  have evolutionary histories that match the  $z_{obs} = 0$  curve out to a lookback times of 3-4 gigayears. If star formation in cluster galaxies is indeed fueled by recent merging in the dark matter component of the cluster, we would expect that a small fraction of clusters present at  $z = 0.4$  to appear very similar to clusters seen today. One well-known observational example is the  $z=0.5$  cluster CL0016+16 which contains few, if any, blue cluster members (Koo 1981). Larger observational samples will be needed before any quantitative comparison can be made with theory.

### 3 Models for Star Formation in Cluster Galaxies

In this section, we explore two simple models for the rate at which stars form in cluster galaxies. This first model is motivated by the “infall” picture of Dressler & Gunn (1983). We assume that stars form at a constant rate in galaxies until they are incorporated into larger systems, such as groups or clusters. Once the galaxy has been accreted, we assume that star formation ceases because gas is stripped from the galaxy due to the ram-pressure of the intracluster medium. In this model, the epoch at which galaxies are accreted by larger systems delineates the transition between active star formation and the “post-starburst” phase discussed by Dressler & Gunn (1983). For illustrative purposes, we will assume that a galaxy can form stars so long as it is contained in a halo with mass in the range  $10^{11} - 10^{13}M_{\odot}$ . In figure 3, we show the mass fraction of the cluster which is contained in halos in this mass range as a function of lookback time for a  $10^{15}M_{\odot}$  cluster observed at  $z_{obs} = 0, 0.07, 0.15, 0.2, 0.3$  and  $0.4$ . It is clear that star formation occurs at earlier lookback times for clusters seen today than for clusters observed at high redshift. Again, this simply follows from the fact that high redshift clusters assemble later. We conclude that infall-driven star formation will lead to a trend consistent with the Butcher-Oemler effect.

The second model is motivated by the interactions/mergers picture favoured by Lavery & Henry (1986) and Lacey & Silk (1991) in which encounters between close pairs of galaxies are responsible for the observed star formation in cluster galaxies at high redshift. We assume that a merger between galaxy-sized halos of roughly equal mass results in a burst of star formation. In figure 4, we show the rate at which galaxy-sized progenitors of a  $10^{15}M_{\odot}$  cluster merge with each other as a function of lookback time, again for clusters with  $z_{obs} = 0, 0.07, 0.15, 0.3, 0.4$  and  $0.4$ . We plot the fraction of the mass of the cluster per gigayear in halos that undergo a merger with another object of at least half its mass, and we restrict the halos to be in the mass range  $10^{11} - 10^{13}M_{\odot}$ . Once again, we see that the inferred star formation rate peaks at

smaller lookback times for clusters observed at high redshift than for clusters seen today. A higher incidence of interacting galaxies in high redshift clusters is thus also a natural outcome of hierarchical clustering theory. It should be noted that in our picture, merging occurs in lower mass groups *before* the cluster is assembled. Not much merging is believed to occur once the cluster has formed because of the high relative velocities between pairs of galaxies.

One popular idea is that mergers between galaxies of nearly equal mass lead to the transformation of disk galaxies into ellipticals or the spheroidal bulges of spirals. We can transform the instantaneous merging rates shown in figure 4 into a plot of the cumulative mass fraction of the cluster contained in merged remnants as a function of lookback time (figure 5). If we assume that a large fraction of the stars in an elliptical galaxy form in a burst during the merging event, we infer from figure 5 that elliptical galaxies in high redshift clusters have substantially younger stellar populations than cluster ellipticals seen today. This trend also seems to be apparent in the observational data. Aragon-Salamanca et al (1993) present evidence for a systematic bluing of the reddest galaxies in rich clusters as a function of redshift. This trend is in agreement with studies of the evolution of the amplitude of the 4000 Å break in red cluster galaxies by Dressler & Gunn (1990).

We have shown that both the infall-driven and merging-driven pictures of star formation lead to trends consistent with observations. In practice, both effects are likely to be important in explaining cluster evolution. We can address this question explicitly by comparing the mass fraction of the cluster transformed into merger remnants during the final 3 gigayears of its evolutionary history, with the mass fraction in galaxy-sized halos which have never merged, but have been accreted onto a larger system during the same time. We find that the two mass fractions are approximately equal for all values of  $z_{obs}$ . We conclude that *both* the infall and merging mechanisms are likely to be responsible for the blue, actively star-forming galaxies seen in rich clusters at all redshifts.

## 4 Dependence on Cosmology

As we have discussed, the trend in the evolutionary behaviour of rich clusters with redshift is intrinsic to hierarchical clustering scenarios and occurs because rich clusters are on the high mass tail of the distribution of collapsed objects in the universe today. One of the important tests of any model of structure formation is that it be able to reproduce the observed abundance of rich clusters. So it should come as no surprise that the trends we have discussed in the previous sections are much the same for most realistic choices of cosmological parameters. What does turn out to be sensitive to the choice of cosmological model is the epoch at which processes such as galaxy merging and infall can be expected to occur.

Let us take, for example, the case of a low density ( $\Omega = 0.2$ ) CDM model. Structure forms considerably earlier in a low density universe. By the present day, the growth of perturbations has slowed considerably and much less merging of dark matter halos will be taking place. In addition, the overall age of the universe is a factor of a third larger. In figure 6, we show the cumulative mass fraction of a  $10^{15}M_{\odot}$  cluster in merger remnants as a function of lookback

time. The curves in this figure are calculated exactly the same way as described for figure 5. Comparing figure 6 to figure 5, we see that all the curves are now shifted to much higher lookback times. In an open universe elliptical galaxies form considerably earlier and there is much less merging going on at late evolutionary times in the cluster. At an observed redshift of 0.4, only 2% of the cluster mass has been involved in a major merging event over the past 3 gigayears in the  $\Omega = 0.2$  CDM model, as opposed to 16% for the  $\Omega = 1$  model. In figure 7, we show the prediction for the fraction of the cluster in star-forming units in the “infall” picture discussed in section 3. This diagram is the analogue of figure 3. We see that star formation in the cluster now peaks at much higher lookback times and that even at  $z_{obs} = 0.4$ , relatively little star formation occurs during the last few gigayears of the cluster’s history. Conversely, models with late structure formation, such as mixed dark matter models, lead to a prediction of more recent merging and star formation activity in cluster galaxies. One obvious way to constrain cosmological parameters, is to make use of the new high resolution imaging techniques to determine, as a function of redshift, what fraction of bright cluster galaxies can be classified as interacting systems, and compare this with our predicted halo merging rates. Observational studies along these lines are currently underway. Another sensitive test of cosmology would be the observed colour evolution of elliptical galaxies in clusters, especially at high redshift. Models with late structure formation such as MDM or high-bias CDM are predict that at redshifts greater than 1, rich clusters should contain almost no luminous elliptical galaxies with old stellar populations.

## 5 Conclusions

We have shown that the rapid evolution in the fraction of blue, star-forming galaxies seen in rich clusters between the present day and redshifts of around 0.4 can be explained very simply if structure formation in the universe occurs hierarchically. In hierarchical clustering models, structure evolves to form larger and larger mass systems with time. A rich cluster observed at  $z = 0.4$  *cannot* be regarded as the direct progenitor of a cluster of similar richness seen today. High redshift rich clusters are much rarer systems and consequently have had different evolutionary histories to those of rich clusters today. They assemble later and undergo more merging at late times. We have explored the predictions of two models of star formation in cluster galaxies:

1. A model in which star formation is triggered by galaxy interactions and mergers.
2. A model in which star formation occurs only in isolated galaxies and ceases once galaxies are accreted onto larger systems such as groups and clusters.

We show that both models lead to trends consistent with the observed Butcher-Oemler effect. We also show that in the hierarchical picture, both galaxy infall and merging are important during the last few gigayears of cluster evolution. The observed star formation in high redshift cluster galaxies is most likely explained by both mechanisms. We have also shown that it is

a prediction of hierarchical clustering theory that the strength of the Butcher-Oemler effect should correlate with the mass (or richness) of the galaxy cluster or group, with more massive systems exhibiting a larger effect. In addition, the strength of the Butcher-Oemler effect should increase with redshift. Finally, we have explored the effect of the choice of cosmological initial conditions on our predictions for cluster evolution. The most dramatic differences are found in low-density models, which predict considerable less recent star formation and merging activity in rich clusters at *all* redshifts, than models with  $\Omega = 1$ .

There is no doubt that observational data on high redshift galaxy clusters will improve very significantly over the next few years. High resolution imaging of clusters by the recently repaired Hubble Space Telescope is currently underway. These studies will provide much more reliable statistical information about cluster galaxy properties, such as morphology, and the frequency of the incidence of interacting systems in clusters. On the theoretical side, the next obvious step would be to combine our Monte-Carlo models of cluster formation with spectrophotometric population synthesis models in order to make detailed comparisons with the data. It seems promising that this combination of approaches will help constrain cosmological models and significantly improve our understanding of the physical processes that regulate galaxy formation in clusters.

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## Figure Captions

**Figure 1:** The evolution of the mass of the most massive progenitor of a halo as a function of lookback time. We plot the logarithm of the mass of the progenitor divided by the mass of the halo as a function of lookback time in gigayears, for halos of fixed mass that are assembled at redshifts 0, 0.07, 0.15, 0.2 0.3 and 0.4. The curves represent averages over 50 Monte-Carlo realizations of the halo merging history. We show results for halos of three different masses. a)  $10^{15}M_{\odot}$  b) $10^{13}M_{\odot}$  c) $10^{12}M_{\odot}$  .

**Figure 2:** The scatter in the evolutionary history of a  $10^{15}M_{\odot}$  cluster. As in figure 1, we show the evolution of the mass of the largest cluster progenitor. The thin lines show 30 individual evolutionary histories for clusters assembled at  $z=0.4$ . The thick solid line shows the *average* evolutionary history of a cluster assembled at  $z=0.4$ . The thick dashed line shows the average evolutionary history of a cluster with the same mass that is assembled today.

**Figure 3:** The mass fraction of a  $10^{15}M_{\odot}$  cluster that is in halos with masses in the range  $10^{11} - 10^{13}M_{\odot}$ , plotted as a function of lookback time. Solid, dotted, short-dashed, long-dashed, short-dashed-dotted and long-dashed-dotted curves are for clusters observed at redshifts 0, 0.07, 0.15, 0.2, 0.3 and 0.4, respectively.

**Figure 4:** The mass fraction (per gigayear) of a  $10^{15}M_{\odot}$  cluster contributed by halos undergoing a merger with objects of at least half their mass, plotted as a function of lookback time. Halos have masses in the range  $10^{11} - 10^{13}M_{\odot}$ . Explanation of the line types is as given in figure 3.

**Figure 5:** The cumulative mass fraction of a  $10^{15}M_{\odot}$  cluster contributed by halos in the mass range  $10^{11} - 10^{13}M_{\odot}$  that have undergone major mergers, plotted as a function of lookback time. Explanation of the line types is as given in figure 3.

**Figure 6:** The cumulative mass fraction of a cluster in merger remnants (as in figure 5), plotted as a function of lookback time for a cold dark matter model with  $\Omega = 0.2$ . Explanation of the line types is as given in figure 3.

**Figure 7:** The mass fraction of a cluster in galaxy-sized halos (as in figure 3), plotted as a function of lookback time for a cold dark matter model with  $\Omega = 0.2$ . Explanation of the line types is as given in figure 3.